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LONG PERIOD SEISMOLOGICAL RESEARCH PROGRAM

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Lamont-Doherty Geological Observatory

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During the past six months, the primary emphasis of the research program has shifted to detailed studies of the excitation and propagation characteristics of surface waves from events in central Asia as observed at the high-gain long-period sites. Preliminary results from observations at Chiang Mai (CHG) show that the complexity of the surface wave signals from many events in the Tadzhik-Kirgiz region is due to the efficient generation of higher mode energy, rather than multi-pathing of the fundamental mode. There are multiple arrivals of energy of the same frequency, but moving-window analysis of the records indicate

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that the anomalous arrivals travel faster than the expected direct arrival of the fundamental mode. Therefore, these arrivals cannot be reflected or refracted fundamental mode energy. The excitation of the higher modes is very sensitive to depth of source and thus the ratio of higher mode energy to fundamental mode may be useful in determining focal depth. As expected, a signal from an explosion in Kazakh has no appreciable higher mode energy. A study of earth noise at the HGLP stations has demonstrated the existance of transient, very long-period microseisms. Detailed spectral analysis of records during intense microseism storms revealed unusual 35 to 40 sec period energy, apparently propagating as retrograde, elliptical Rayleigh waves. The source appears to be non-linear interaction of ocean waves during the storms in the North Atlantic. Tests for non-linear instrument response were negative, indicating that the observations represent true ground motion.

LAMONT-DOHERTY GEOLOGICAL OBSERVATORY
OF COLUMBIA UNIVERSITY
PALISADES, NEW YORK 10964

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SUMMARY

During the past six months, the primary emphasis of the research program has shifted to detailed studies of the excitation and propagation characteristics of surface waves from events in central Asia as observed at the high-gain long-period sites. Preliminary results from observations at Chiang Mai (CHG) show that the complexity of the surface wave signals from many events in the Tadzhik-Kirgiz region is due to the efficient generation of higher mode energy, rather than multipathing of the fundamental mode. There are multiple arrivals of energy of the same frequency, but moving-window analysis of the records indicates that the anomalous arrivals travel faster than the expected direct arrival of the fundamental mode. Therefore, these arrivals cannot be reflected or refracted fundamental mode energy. The excitation of the higher modes is very sensitive to depth of source and thus the ratio of higher mode energy to fundamental mode may be useful in determining focal depth. As expected, a signal from an explosion in Kazakh has no appreciable higher mode energy.

A study of earth noise at the HGLP stations has demonstrated the existance of transient, very-long-period microseisms. Detailed spectral analysis of records during intense microseism storms revealed unusual 35 to 40 sec period energy, apparently propagating as retrograde, elliptical Rayleigh waves. The source appears to be non-linear interaction of ocean waves

during storms in the North Atlantic. Tests for non-linear instrument response were negative, indicating that the observations represent true ground motion.

I. STATION MAINTENANCE

During the past six months of the subject contract, the high-gain station at Ogdensburg, New Jersey (OGD) was maintained in constant operation. In late June, the oscillator-discriminator electronics for the north/south seismometer began to function in an erratic manner. A technician was sent from the Albuquerque Seismological Center to replace the unit and to recalibrate the entire system with the assistance of Lamont personnel. The digital recorder was also checked and adjusted at this time. This was the first time the instrument pressure tanks had been opened since late in 1971, resulting in a disturbance of the thermal environment. The N/S component is still instrumentally noisy, but is gradually improving. Both the seismograms and digital data from OGD to the present time have been shipped to ASC in New Mexico.

II. RESULTS OF THE DATA ANALYSIS

A. Surface waves from events in Central Asia

The primary emphasis of the research program has shifted to detailed studies of the excitation and propagation characteristics of surface waves from events in central Asia as observed at the high-gain sites. The ultimate goal of this program is to

learn enough about propagation effects in this region, such as phase and group velocities, attenuation, and multi-pathing, to permit the use of the complete long-period record, including higher modes, in studying the depth and mechanism of seismic sources. Preliminary results are encouraging, suggesting that it is possible and practical to unravel, in detail, the effects of source, path, and receivers. A number of interesting features can be illustrated by examining portions of three seismograms recorded at Chiang Mai (CHG), Thailand.

The first record, number 1 in Figure 1, is typical of many vertical, long-period records of earthquakes from the Tadzhik-Kirgiz region of southern USSR. It is very complex, with apparent multiple arrivals of energy of the same frequency. The first signal shown is the S-wave, followed by the clear arrival of a higher mode Rayleigh wave. It was originally thought that the complexity of the records for events in this area was due to multi-path propagation in the tectonically active, highly mountainous, and laterally heterogeneous region between Kirgiz and Chiang Mai. However, it can be shown that the efficient generation and propagation of higher mode energy, rather than multipathing of the fundamental mode, is responsible for the complexity.

The second seismogram tracing (no. 2 in Figure 1) from an event to the WSW of the first one (Figure 2) is very simple, showing a clear, normally-dispersed, fundamental mode Rayleigh wave. There is very little higher mode energy present. The

fact that a surface wave can be as simple as it is for event 2, despite the complex tectonic path, implies that the primary difference between the two recordings is a source effect, not a propagation effect. This implication is confirmed by moving-window-analysis (Landisman et al., 1969) of the records. In Figures 3 and 4, contour levels of equal energy are plotted versus period and group arrival time (velocity). Each frequency has been normalized independently, so that the contours represent levels of equal energy relative to the maximum energy observed for each period. The plot for event 2 (Figure 3) is very simple, showing that the strongest signal throughout the 10 to 100 sec range is the fundamental mode. Some higher mode signal in the 10-15 sec range arrives with a group velocity of about 3.9 km/sec, but the amplitude is reduced about 10 db from the peak. In contrast, the higher mode with group velocity of 3.9 km/sec is the strongest arrival of energy for event 1 in the 15 to 20 sec range. Yet, despite the complexity of the seismogram, the same fundamental mode signal can be followed in Figure 4 as was found for record 2. Comparing Figure 4 with Figure 3 shows that the multiple arrivals of energy are due to signals coming in before the normal arrival of the fundamental mode wave of the same frequency. Consequently, the multiplicity cannot be due to multi-pathing of the fundamental mode, which would result in late arrivals.

Multi-pathing is not a problem, but matched-filtering (cross-correlation using master events) to improve the signal-to-noise ratio is still not practical due to the wide variability of higher mode excitation. However, the arrivals are separated on the frequency-time plots, so that time-variable filtering can recover individual modes, allowing precise measurements of phase velocity. Conversely, once the phase velocities are known, the apparent initial phase of the source can be used to help determine the depth and focal mechanism of an event. The wide-variability in higher mode excitation is in itself a valuable diagnostic tool for depth determination. Panza et al. (1973) have shown that for surface focus events, the fundamental mode is dominant at all periods. Deeper sources are more efficient generators of the higher modes at frequencies where most of the energy is trapped within the crustal layer. The frequency and mode which is excited to the greatest degree depends on the exact depth and mechanism of the source. Explosions should always generate predominantly fundamental mode waves due to their shallow hypocenter. This is illustrated by the data in trace 3 and Figure 5 which is from an explosion in Kazakh (Figure 2). The instrumental response for this record is somewhat different due to filtering at the station, but the effect of filtering is totally removed from Figure 5 by the method we have used of individually normalizing each frequency. As expected, there is no indication of any significant higher mode

energy, so the excitation of higher modes may be a useful tool for distinguishing earthquakes from explosions. Very shallow earthquakes are efficient generators of surface waves, so it should be possible to distinguish them from explosions on an M_s-m_b basis or by using the apparent initial phase of the fundamental mode waves.

It must be emphasized that these examples of the results found so far are just preliminary steps in a study that involves determination of focal mechanisms, crustal structure, relative excitation of the modes, phase and group velocity, and scattering and attenuation effects.

B. Very-long-period microseisms

The average spectrum of earth noise between periods of about 2 and 200 sec is now well determined and its sources reasonably well understood. The dominant source of earth noise at periods below about 30 sec is known to be swell-generated microseisms, while the dominant source at periods greater than 40 sec is thought to be non-propagating ground motion of atmospheric origin (Savino *et al.*, 1972).

The double frequency (DF) microseisms (period of about 6 to 8 sec) are surface waves generated by the non-linear interaction of trains of oppositely travelling ocean waves (Longuet-Higgins, 1950; Hasselmann, 1963). The primary frequency (PF) microseisms (period of about 12 to 17 sec) have been described by Haubrich and McCamy (1969) as surface wave noise generated by ocean waves near the coast, particularly in the vicinity of

large storms. The sources for transient background noise phenomena are not as well understood. Oliver (1962) studied a rare 27 sec PF microseism storm, Haubrich and McCamy found DF surface waves generated in the wake of an unusually swift tropical storm far at sea, and Savino and Rynn (1972) studied the ground displacements produced by slow-speed gravity waves from a pressure disturbance of meteorological origin.

Recently, Murphy and McCamy made an extraordinary observation of 35 to 40 sec Rayleigh wave microseisms at the Kongsberg (KON) high-gain, long-period seismograph station. The Kongsberg station is well situated in southern Norway to record DF and PF microseisms generated by gales in the North Atlantic. During the International Seismic Month (20 Feb. - 19 March, 1972), the power spectra was calculated for nearly every day. For the days during which severe DF and PF microseisms were absent, the power spectra display a pronounced minimum between about 30 and 45 sec, but for four days during which severe DF and PF microseism storms were present the minimum was less pronounced and the level was raised about 10 db.

The coherence between the vertical and north/south (N/S) components during one of the four severe DF and PF microseism storms is significant for the majority of periods less than 40 sec; and, although the phase spectrum between the same two components does not show the 90° or 270° relation between them as expected for Rayleigh waves, there is a trend in the data toward 90°

as the period decreases. The departure of the phase spectrum from 90° or 270° does not rule out Rayleigh wave type ground for at least two reasons. The phase spectrum has not been corrected for a possible changing phase shift between the two components and an accurate phase spectrum is expected only for those periods with near-unity coherence. (If the Rayleigh wave motion is broad beam or combined with significant Love wave motion, unity coherence is not expected.)

The signal from the three components for a portion of the time sample was passed through a 6-pole, low-pass, Butterworth filter with a corner period of 35 sec. A plot of these traces shows three things: reasonably good correlation between the vertical and N/S traces, the peaks of about 40 sec signal on the vertical trace lead the peaks on the N/S trace, and the vertical and E/W traces correlate far less well.

There was no significant coherence between the vertical and E/W components for this same period of time. These three observations of significant coherence between vertical and N/S component, an approximately 90° phase shift between vertical and N/S component with vertical leading, and no significant coherence between vertical and E/W components, are good indicators that what we have observed are 35 to 40 sec Rayleigh wave microseisms with retrograde motion coming from a source north of KON. A check of the surface weather charts for the northern hemisphere shows that there is a large low pressure system north of KON

for the proper time interval, that is, allowing for ocean wave propagation from the storm to the coast line. It is likely that this storm is the source of the ocean wave energy responsible for the DF and PF microseism storm. The possibility that the observed signal was the coda of a large earthquake was eliminated by checking the list of earthquakes for the International Seismic Month and by searching for similar noise at the same time at the Toledo and Ogdensburg HGLP stations. No large earthquake is listed near the time of the microseism storms, and the signals were not observed as far away as TOC or OGD.

C. Test for non-linear instrument response

The observation of 35 to 40 sec noise during intense microseism storms initially suggested the possibility of instrumental non-linearity. If the relatively short-period ground motion associated with microseisms could generate this long-period signal through non-linear coupling, it would significantly affect the ability to recover small signals from the coda of large events or from background microseism noise. Two methods were used to demonstrate that the observed signal was due to true long-period ground motion. First, a bispectral analysis of selected time periods was performed. The bispectrum tests to see if there is coherent energy present at $(f_1 + f_2)$ or $(f_1 - f_2)$ for two frequencies f_1 and f_2. The bispectra did not differ significantly from zero, indicating that non-linear response was probably neglibible. As a further test, an active test on the

HGLP system at Ogdensburg, N.J. was carried out. Driving the seismometer boom with an appropriately large 7-sec sine wave through the calibration coils produced no spurious energy at 40 sec. We conclude that within the normal dynamic range of the instrument, non-linearity is unimportant.

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FIGURE CAPTIONS

Figure 1 Rayleigh waves from events in central Asia. Each recording is normalized to give the same maximum amplitude. Trace 1 from earthquake on June 5, 1971; trace 2 from earthquake on July 24, 1971; and trace 3 from explosion on April 25, 1971.

Figure 2 Paths from epicenters to the seismograph station at Chiang Mai, Thailand for the events shown in Figure 1.

Figure 3 Moving window analysis of trace 2. Each frequency is normalized independently. Equal energy contour at boundary of dark region is down 1.5 db from peak amplitude. Boundary of light region reduced 10 db from peak.

Figure 4 Moving window analysis of trace 1. The multiple arrivals of energy are due to the S-wave and higher modes.

Figure 5 Moving window analysis of explosion trace 3. Note the absence of higher mode energy.

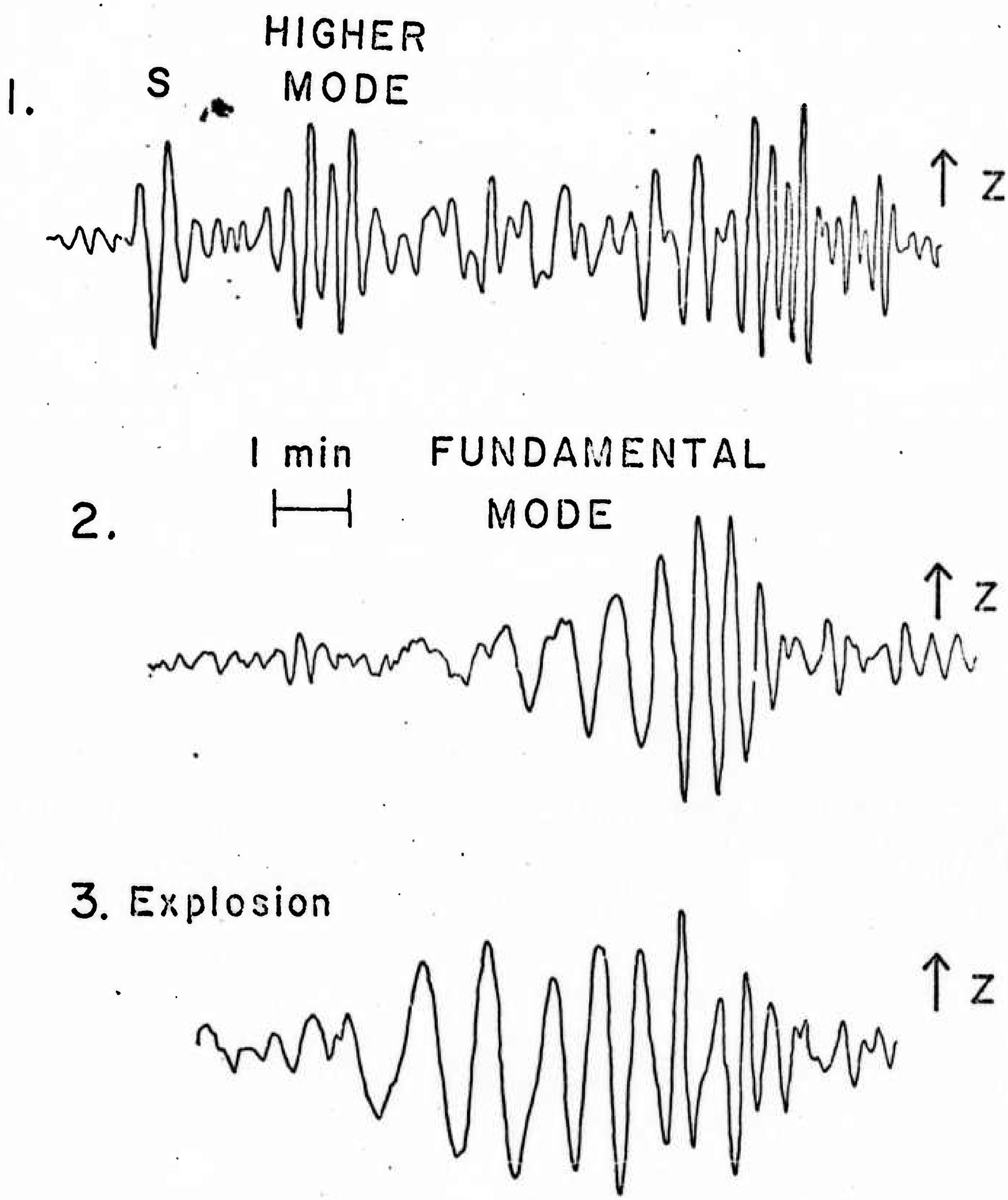


Figure 1

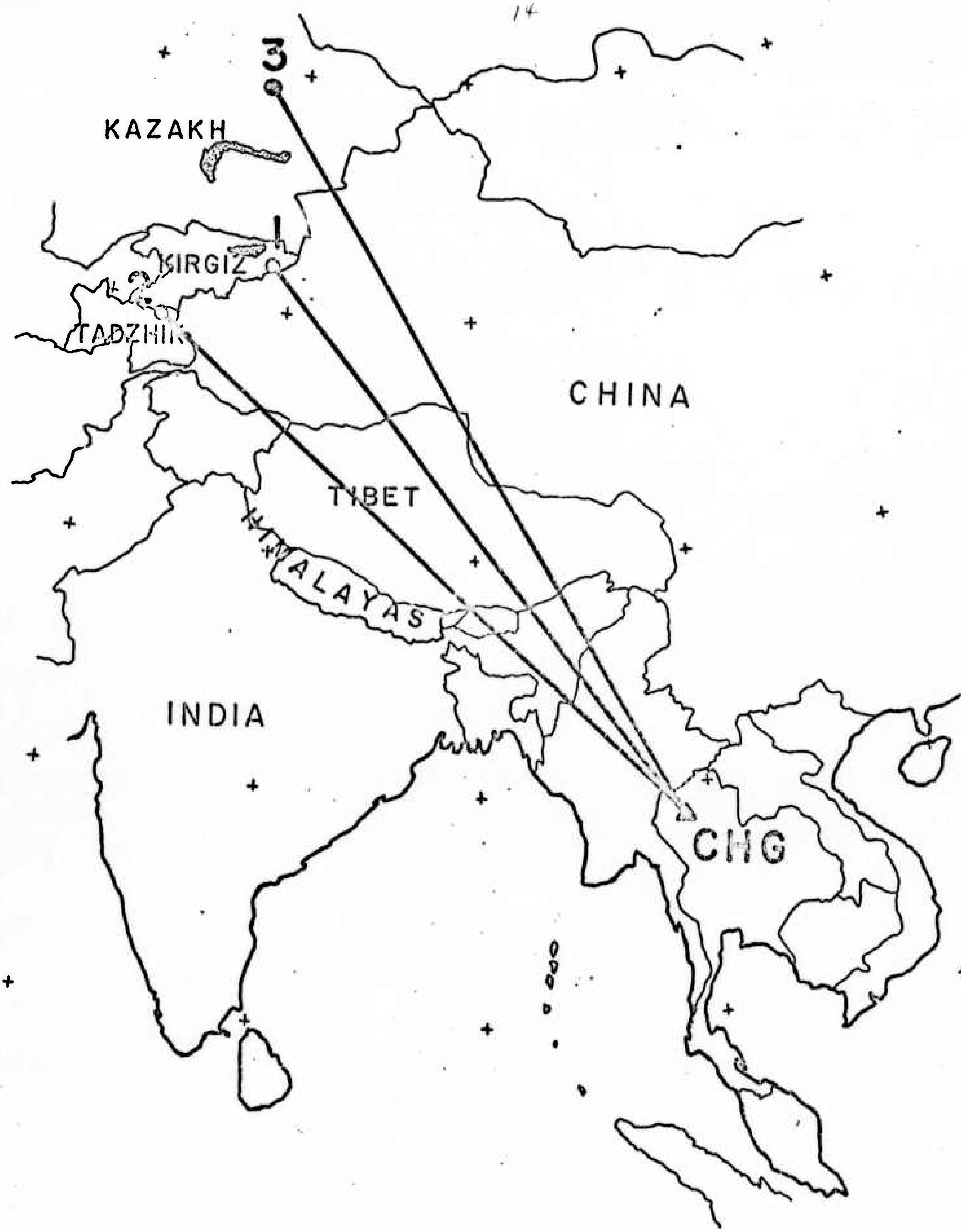


Figure 2

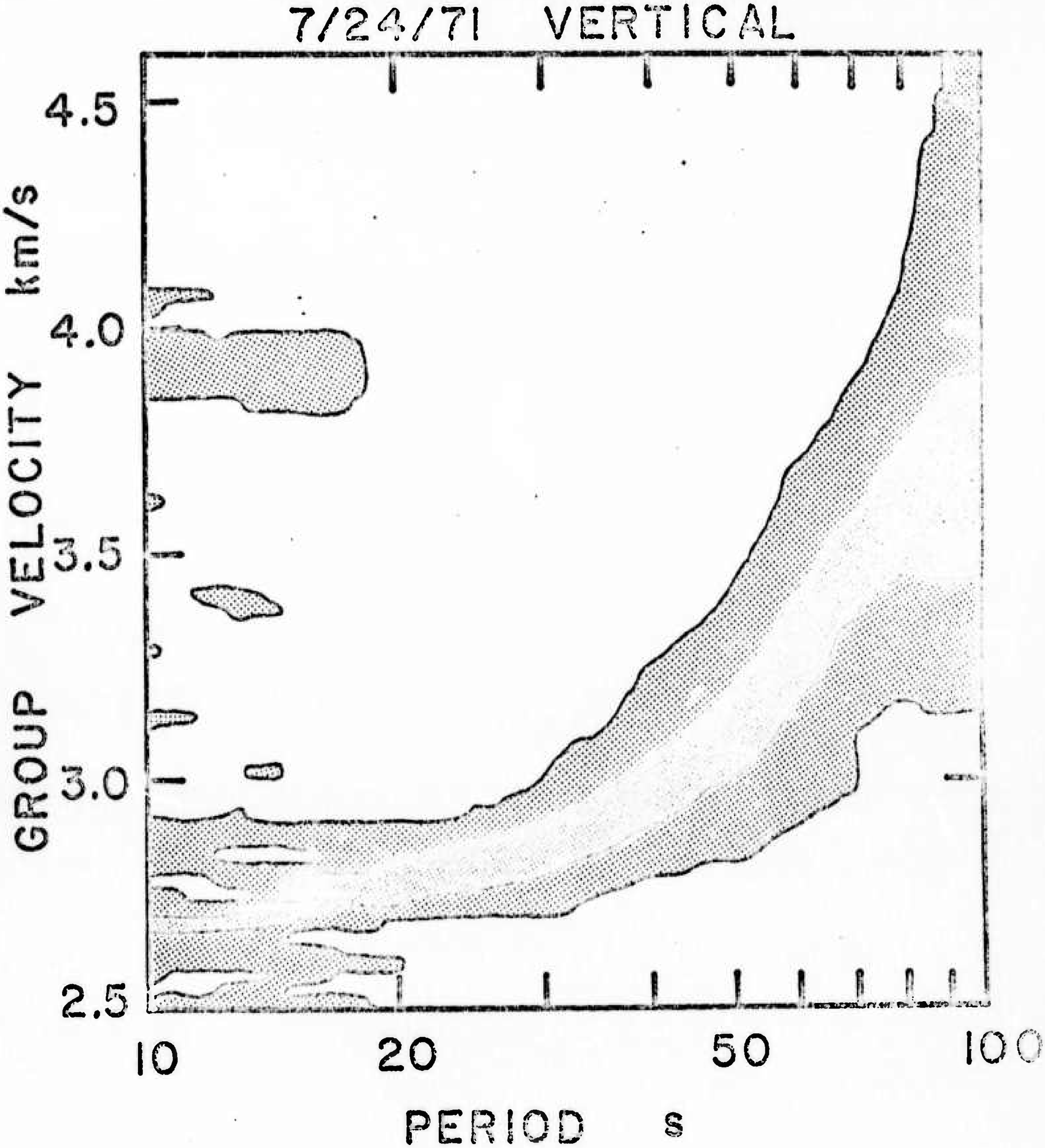
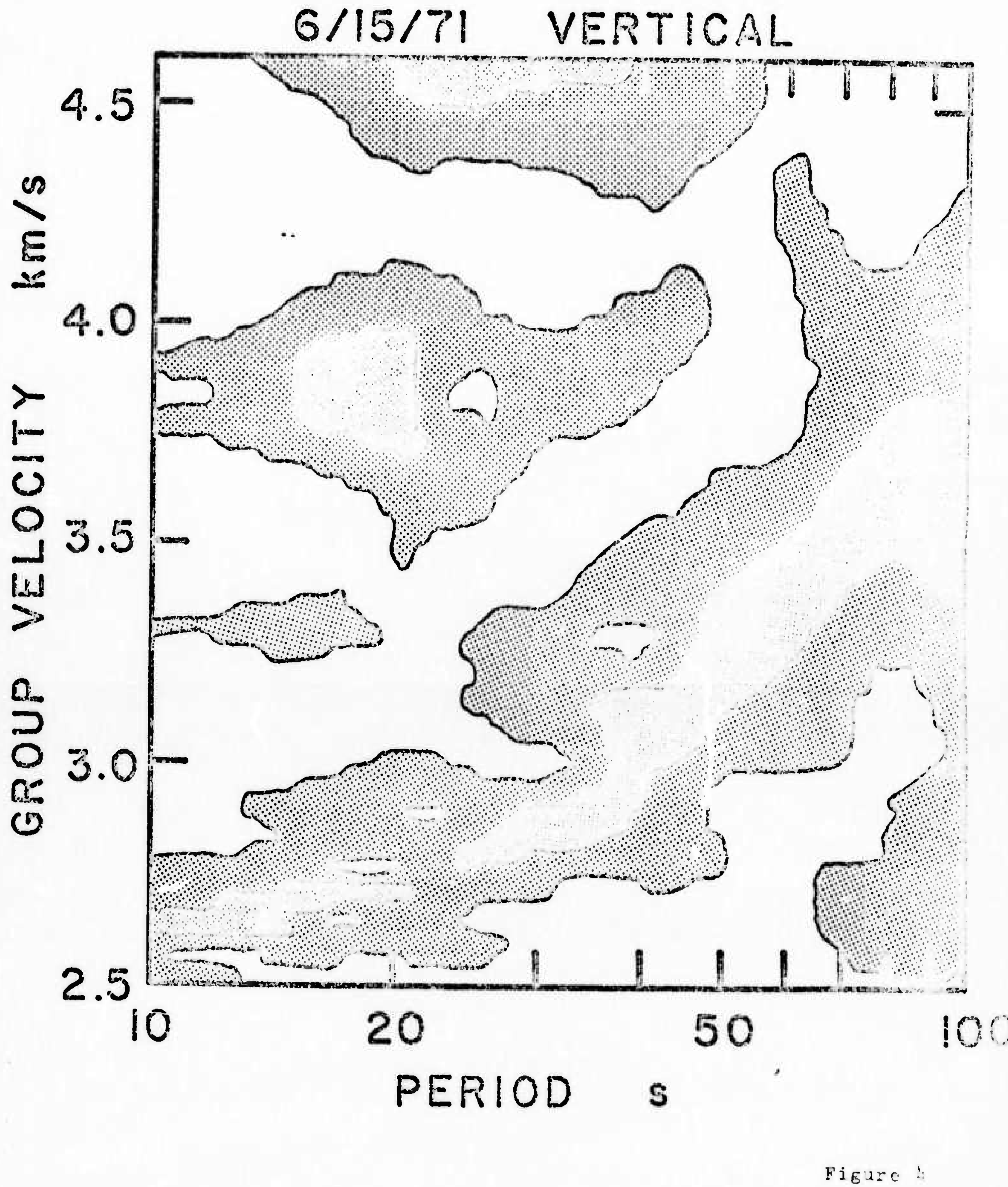

7/24/71 VERTICAL
GROUP VELOCITY km/s
4.5
4.0
3.5
3.0
2.5
10
20
50
100
PERIOD s

Figure 3


6/15/71 VERTICAL
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4.5
4.0
3.5
3.0
2.5
10
20
50
100
PERIOD s

Figure 4

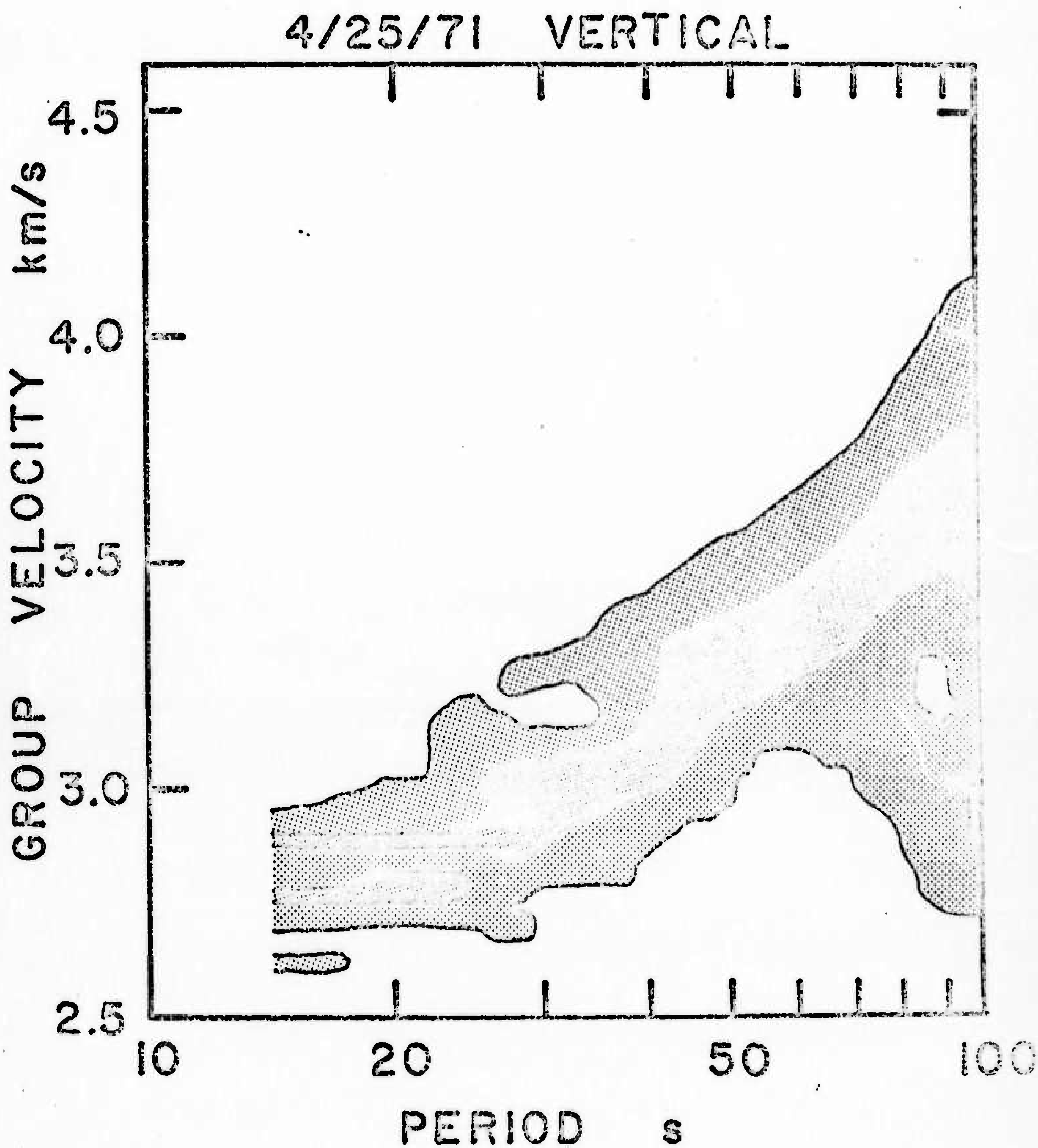
4/25/71 VERTICAL
GROUP VELOCITY km/s
4.5
4.0
3.5
3.0
2.5
10
20
50
100
PERIOD s

Figure 5